Reaction mechanisms in ^{24}Mg+^{12}C and ^{32}S+^{24}Mg

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Abstract. The occurence of "exotic" shapes in light N=Z α-like nuclei is investigated for ^{24}Mg+^{12}C and ^{32}S+^{24}Mg. Various approaches of superdeformed and hyperdeformed bands associated with quasimolecular resonant structures with low spin are presented. For both reactions, exclusive data were collected with the Binary Reaction Spectrometer in coincidence with EUROBALL IV installed at the VIVITRON Tandem facility of Strasbourg. Specific structures with large deformation were selectively populated in binary reactions and their associated γ-decays studied. The analysis of the binary and ternary reaction channels is discussed.

Keywords: Complete spectroscopy, superdeformation, hyperdeformation, ternary fission
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INTRODUCTION

The observation of resonant structures in the excitation functions for various combinations of light α-cluster (N = Z) nuclei in the energy regime from the barrier up to regions with excitation energies of E$_x$ = 20-50 MeV remains a subject of contemporary debate [1, 2]. These resonances have been interpreted in terms of nuclear molecules [1]. The question whether quasimolecular resonances always represent true cluster states in the compound systems, or whether they may also simply reflect scattering states in the ion-ion potential is still unresolved [1, 2]. In many cases, these resonant structures have been associated with strongly-deformed shapes and with clustering phenomena, predicted from the Nilsson-Strutinsky approach [3, 4], the cranked α-cluster model [5], or other mean-field calculations [6, 7]. Of particular interest is the relationship between superdeformation (SD) and nuclear molecules [8, 9, 10], since nuclear shapes with major-to-minor axis ratios of 2:1 have the typical ellipsoidal elongation (with quadrupole deformation parameter $\beta_2 \approx 0.6$) for light nuclei [4]. Furthermore, the structure of possible octupole-unstable 3:1 nuclear shapes (with $\beta_2 \approx 1.0$) - hyperdeformation (HD) - for actinide nuclei has also been widely discussed [4, 10, 11] in terms of clustering phenomena. A typical example of the possible link between quasimolecular bands and SD/HD
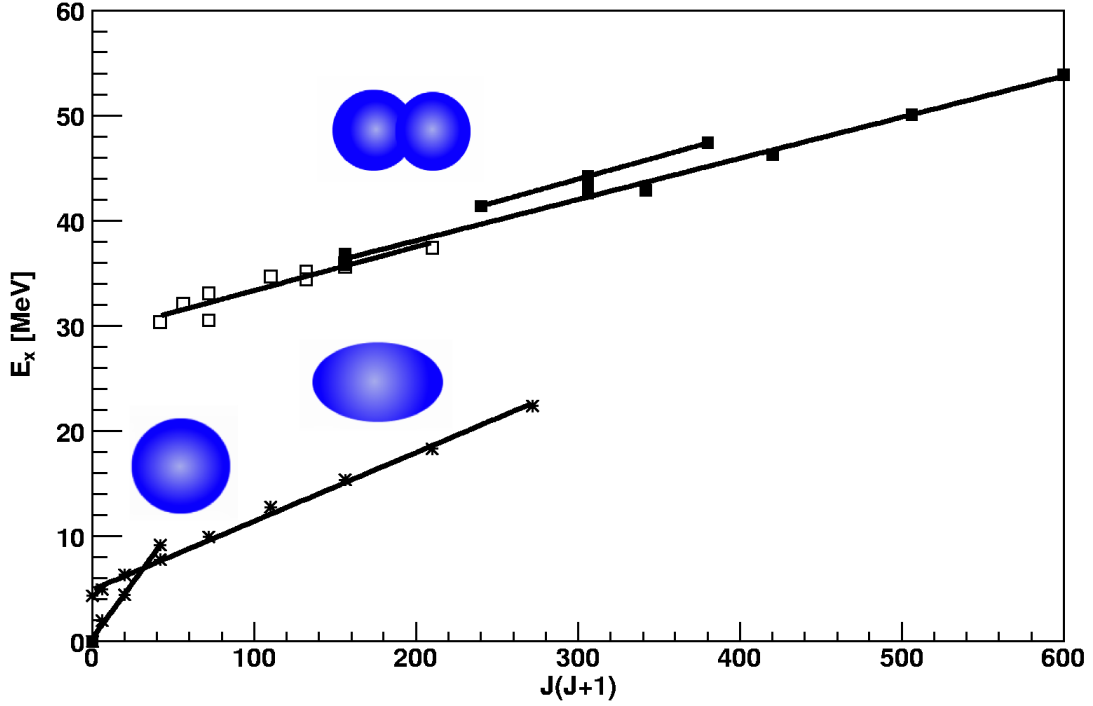
FIGURE 1. Rotational bands and deformed shapes in ^{36}Ar. Energies of the g.s. (spherical shape) and SD bands [15] (ellipsoidal shape), and the energies of HD band from the quasimolecular resonances observed in the ^{12}C+^{24}Mg (open rectangles) and ^{16}O+^{20}Ne (full rectangles) reactions (dinuclear shape) are plotted as a function of J(J+1) [12].

shapes [10, 12] is given in Fig. 1 for ^{36}Ar [12].

Large quadrupole deformations (β_2 = 0.6-1.0) and α-clustering in light N = Z nuclei are known to be general phenomena at low excitation energy. For high angular momenta and higher excitation energies, very elongated shapes are expected [13] to occur in α-like nuclei for A$_{CN}$ = 20-60. These predictions come from the generalized liquid-drop model, taking into account the proximity energy and quasi-molecular shapes [13] (as in the cluster models [5, 14]). In fact, highly deformed shapes and SD rotational bands have been recently discovered in several such N = Z nuclei, in particular, ^{36}Ar using γ-ray spectroscopy techniques [15]. HD bands in ^{36}Ar, illustrated in Fig. 1 as quasimolecular bands observed in ^{12}C+^{24}Mg (open rectangles) and ^{16}O+^{20}Ne (full rectangles) reactions [12], and their related ternary clusterizations are predicted theoretically [16]. With the exception of the cluster decays of ^{56}Ni [17, 18] and ^{60}Zn [19, 20] recently studied using charged particle spectroscopy [21], no evidence for ternary breakup has yet been reported [22, 7] in light nuclei; the particle decay of ^{36}Ar SD bands and of other highly excited bands (displayed as stars in Fig. 1) is still unexplored. The main binary reaction (i.e. α-transfer) channel of the ^{24}Mg+^{12}C, for which both resonant effects [12] (see open rectangles in Fig. 1) and orbiting phenomena [22] have been observed, is investigated in this work by using charged particle-γ-ray coincidence techniques. Results on ternary fission in ^{32}S+^{24}Mg are also discussed.
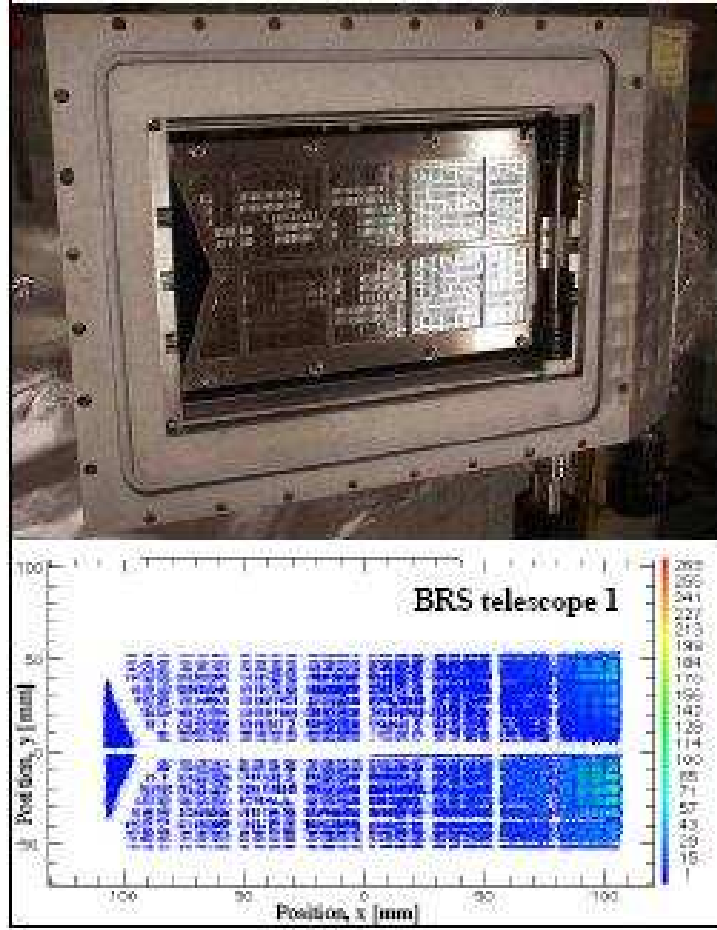
FIGURE 2. Photograph (top) showing a mask in place in front of one arm of the BRS telescope (top); calibrated two-bidimensional position x versus y (in mm) spectrum (bottom) using a 210 μg/cm^2 ^{197}Au target with the 162 MeV ^{32}S beam. The relative intensity (counts) is shown on the side bar.

EXPERIMENTAL RESULTS.

The study of charged particle-γ-ray coincidences in binary reactions in inverse kinematics is a unique tool in the search for extreme shapes related to clustering phenomena. In this paper, we investigate both the ^{24}Mg+^{12}C and the ^{32}S+^{24}Mg reactions by using the Binary Reaction trigger Spectrometer (BRS) [17, 18, 23, 24] in coincidence with the EUROBALL IV (EB) γ-ray spectrometer [18, 23, 24] installed at the VIVITRON Tandem facility of Strasbourg. The ^{24}Mg and ^{32}S beams were produced and accelerated by the VIVITRON with beam intensities kept constant at approximately 5 pnA. For the ^{24}Mg+^{12}C study the targets consisted of 200 μg/cm^2 thick foils of natural C with an incident beam energy of E$_{lab}$ = 130 MeV an excitation energy range up to E* = 30 MeV in ^{24}Mg is covered. For both reactions the BRS, in conjunction with EB, gives access to a novel approach for the study of nuclei at large deformations as described below.
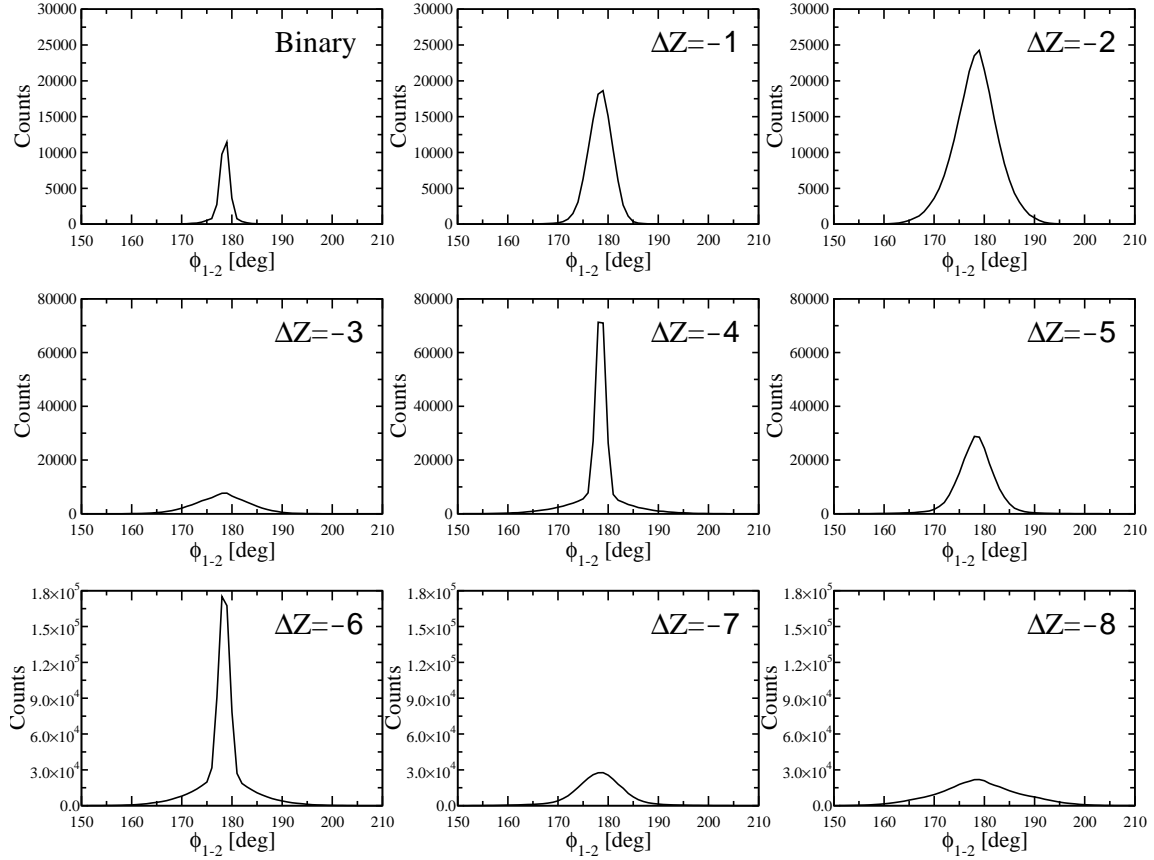
FIGURE 3. Out-of-plane angular correlation yields for binary decay (first spectrum) and for respective non-binary emission channels measured from the ^{32}S+^{24}Mg reaction at 163.5 MeV with different missing charges ΔZ.

DISCUSSION

The BRS associated with EB combines as essential elements two large-area (with a solid angle of 187 msr each) heavy-ion gas-detector telescopes in a kinematical coincidence setup at forward angles. A photograph of one of the BRS telescope is shown in Fig. 2 along with a two-dimensional spectrum obtained with a mask during a ^{32}S+^{197}Au calibration run at 163.5 MeV [18]. The two telescope arms are mounted symmetrically on either side of the beam axis, each covering the forward scattering angle range 12.5°-45.5°, i.e. $\theta = 29° \pm 16.5°$. For this reason the 30 tapered Ge detectors of EB [18, 23, 24] were removed.

Fig. 3 shows out-of-plane angular correlations measured for the ^{32}S+^{24}Mg reaction at 163.5 MeV [17, 18, 21]. A carefull analysis of the fragment total kinetic energies was undertaken to isolate true ternary events from binary fission components due to
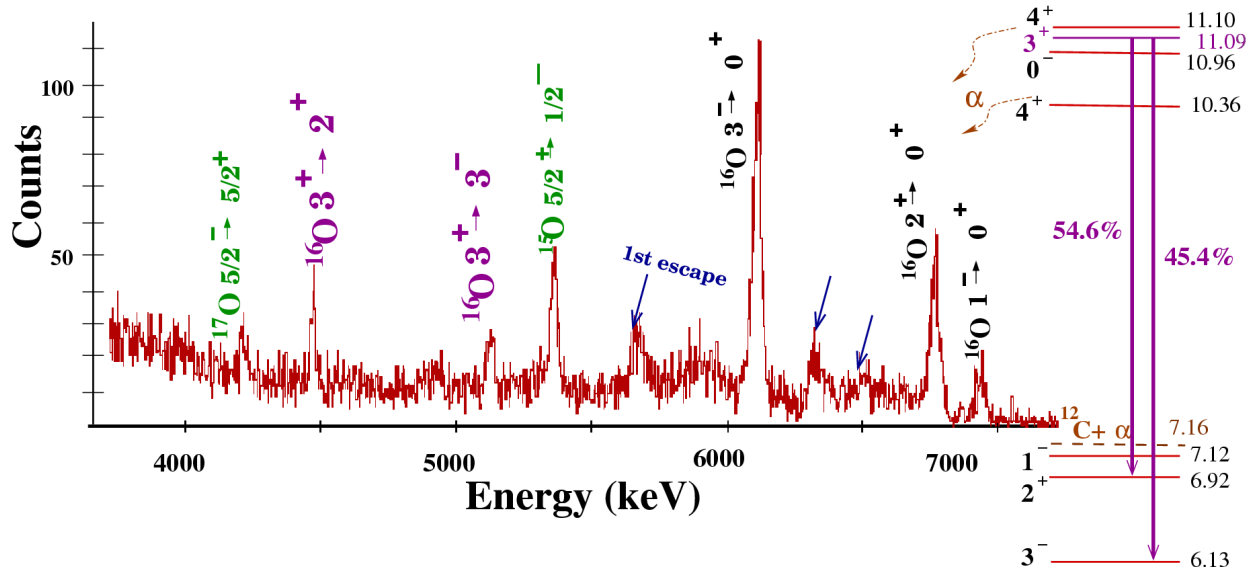
FIGURE 4. ^{16}O high-energy excited states populated in the ^{16}O+^{20}Ne exit-channel of the ^{24}Mg+^{12}C reaction at 130 MeV. Doppler-shift corrections have been applied for O fragments detected in the BRS. The three blue arrows show the respective first escape peak positions of the 6.13 MeV, 6.92 MeV and 7.12 MeV γ-ray transitions in ^{16}O. The new partial level scheme of ^{16}O is plotted in the inset.

significant oxygen and carbon contaminants (see Refs. [18] for more details) having different Q-values. The narrow peak of the first angular correlation with $\Delta Z = 0$ comes from the binary nature of the fragmentation process. The two other narrow distributions, also peaked at 180^0 for missing charges $\Delta Z = -4$ (-2α) and -6 (-3α), define the coplanar (or collinear) ternary fission with a small out-of-plane momentum. The widening of the correlation width as observed with increasing ΔZ for the underlying broad components is well understood as a statistical α-emission process where 1-4α particles are emitted from the fully accelerated fragments.

For the ^{24}Mg+^{12}C α-transfer reaction, the identifications of all γ rays in ^{20}Ne were achieved [24]. Two previously unobserved transitions in ^{16}O from the decay of the 3$^+$ state at 11.09 MeV are clearly visible in the γ-ray spectrum of Fig. 4, have been identified for the first time. The new the partial level scheme is proposed in the inset of Fig. 4. We note that, thanks to the excellent resolving power of the EB+BRS set-up, the respective first escape peak positions of the 6.13 MeV, 6.92 MeV and 7.12 MeV γ-ray transitions in ^{16}O are also apparent in this spectrum.

With appropriate Doppler-shift corrections applied to oxygen fragments identified in the BRS, it has been possible to extend the knowledge of the level scheme of ^{16}O at high energies [25, 26, 27], well above the ^{12}C+α threshold, which is given in Fig. 4 for the sake of comparison. New information has been deduced on branching ratios of the decay of the 3$^+$ state of ^{16}O at 11.085 MeV $\pm$ 3 keV (which does not α-decay because of non-natural parity [27], in contrast to the two neighbouring 4$^+$ states at 10.36 MeV and 11.10 MeV, respectively) to the 2$^+$ state at 6.92 MeV (54.6 $\pm$ 2 %) and a value for the decay width Γ_γ fifty times lower than the one given in the literature [26], it means $\Gamma_{3+} <$

0.23 eV. The third state with non-natural parity (0^-) belonging to the (0^-, 3^+, 4^+) triplet near 11 MeV has a known transition to the 1^- state which is not observed experimentally in our work. This 3^+ state result is important as it is the highest known γ-decaying level for the well studied ^{16}O nucleus [26]. However, other experimental techniques will have to be used in the near future (such as the PARIS/GASPARD projects [28] in preparation for the forthcoming Spiral2 facility at GANIL) to search for the Bose-Einstein Condensation (BEC) α-particle state in ^{16}O (an equivalent α+Hoyle state) predicted to be the 0_6^+ state at about 2 MeV above the 4α-particle breakup threshold [29].

SUMMARY, CONCLUSIONS AND OUTLOOK

The connection of α-clustering, quasimolecular resonances phenomena and extreme deformations (SD, HD, ...) [7, 8, 9, 10, 11, 12] can be discussed in terms of the aspects of γ-ray spectroscopy of binary and/or ternary fragments. Exclusive data were collected with the Binary Reaction Spectrometer (BRS) in coincidence with EUROBALL IV installed at the VIVITRON Tandem facility of Strasbourg. New γ-ray spectroscopy results on ^{16}O from binary alpha-transfer reactions has been obtained from the ^{24}Mg+^{12}C reaction. In ^{32}S+^{24}Mg, ternary events can be interpreted as ternary cluster decay from a ^{56}Ni composite system at high angular momenta through hyper-deformed shapes. The search for extremely elongated configurations (HD) in rapidly rotating medium-mass nuclei, which has been pursued exclusively using γ-spectroscopy, can be performed in conjunction with charged particle spectroscopy.

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